# III. SEA-LEVEL RISE SCIENCE

This chapter includes:

A) Sea-level rise background information and a description of the best available science on the subject
B) Sea-level rise impacts to coastal areas
C) Implications of sea-level rise for coastal resources

It can serve as a source of scientific background information for users of this Guidance document.

## A. BEST AVAILABLE SCIENCE ON SEA-LEVEL RISE

Scientists now widely agree that the climate is changing and that it has led to global increases in temperature and sea level. Global sea-level rise is driven by the expansion of ocean waters as they warm, the addition of freshwater to the ocean from melting land-based ice sheets and glaciers, melting sea ice, and from extractions in groundwater. In the past century, global mean sea level (MSL) has increased by 17 to 21 centimeters (7 to 8 inches) (IPCC, 2013). There are a number of methods for projecting future changes in global sea level, including using extrapolations from historic trends and observations, estimations from physical models, and combinations of observations and modeling, known as semi-empirical methods. For a detailed description of these methods, see Appendix A.

Scientists measure sea level change at the global and local scales. The *Global Sea Level Rise Scenarios for the United States National Climate Assessment* (2012) report provides a set of four global sea-level rise scenarios ranging from 0.2 to 2.0 meters (8 inches to 6.6 feet) reflecting different amounts of future greenhouse gas emissions, ocean warming and ice sheet loss. The low and intermediate-low scenarios assume very significant reductions in greenhouse gas emissions, and limited changes in ocean warming and ice sheet loss. The intermediate-high scenario is based on the average of the high projections from semi-empirical models, which are based on the highest IPCC 4th Assessment Report (AR4) (2007) emissions scenario (A1FI).[12] The highest scenario (2.0 meters) combines the IPCC projections with the maximum possible ice sheet melt that could occur by 2100. Given the recent studies that suggest that glacier and ice sheet loss could significantly contribute to rising sea-levels (e.g. Rahmstorf, 2007 and Vermeer and Rahmstorf, 2009) and evidence that current greenhouse gas emissions are tracking with intermediate AR4 IPCC scenarios (Rahmstorf et al., 2012), the low and intermediate-low scenarios likely under represent future sea-level rise. At the time of this report, these scenarios represent the best available science on global sea-level rise and are designed to be modified for



[12] The IPCC emissions scenarios make assumptions about future changes in population growth, future economic growth and the introduction of clean and efficient technology. The A1FI scenario assumes continued intensive use of fossil fuels, high economic growth, and low population growth that peaks mid-century. The B1 scenario assumes significant reduction in fossil fuel use, an increase in clean technologies, and the same low population growth that peaks mid-century. The A1F1 yields the highest $CO_2$ emissions by 2100 and the B1 scenario yields the lowest. For a complete description of these scenarios, see Appendix A, Section A.4.

local conditions throughout the United States. For California, the NRC 2012 report, described below, provides sea-level rise scenarios that have been refined for use at the regional level.

**Best Available Sea-Level Rise Projections for California**

Tide gauges and satellite observations show that in the past century, mean sea level in California has risen 20 centimeters (8 inches), keeping pace with global rise. In the past 15 years or so, mean sea level in California has remained relatively constant, and has been suppressed due to factors such as offshore winds and other oceanographic complexities. Bromirski et al. (2011 and 2012) postulate that persistent alongshore winds have caused an extended period of offshore upwelling that has both drawn coastal waters offshore and replaced warm surface waters with cooler deep ocean water. Both of these factors cause a drop in sea level that may have cancelled out the sea rise that otherwise would be expected. As the Pacific Decadal Oscillation, wind, and other conditions shift, California sea level will continue rising, likely at an accelerated rate (NRC, 2012, Bromirski et al., 2011, 2012).

Over the coming decades, sea level is projected to increase along much of the California coast by up to 1.7 meters (5.5 feet) from 2000 to 2100, according to the 2012 National Research Council "Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future" report (NRC, 2012).

In March 2013, the Ocean Protection Council adopted final Sea-Level Rise Guidance that established the NRC 2012 report as the best available science on sea-level rise for California (OPC, 2013).[13] Consistent with this guidance, the Coastal Commission will be using and recommends that local governments and applicants use the projections provided in the NRC 2012 report in all relevant local coastal planning and coastal development permitting decisions. The full range of sea-level rise projections is provided below in Table 3. Sea-level rise science is evolving and the Commission will periodically re-examine and update these projections as needed with the release of new scientific reports on sea-level rise. For now, however, the Commission staff recommends these figures as the best available projections of regional sea-level rise in California. The range of sea-level rise projections reflects uncertainties in future greenhouse gas emissions, future changes in the rate of ice sheet melt, and uncertainties related to the data. The low end of the projections is based on the lowest AR4 IPCC future $CO_2$ emissions scenario (B1) and the high end is based on the highest AR4 IPCC emissions scenario (A1FI) (2007). Again, given current greenhouse gas emission levels and projections of future ice sheet loss, the lowest sea-level rise projections likely under represent future sea-level rise (Rahmstorf et al., 2012).

[13] Visit http://www.opc.ca.gov/2009/12/climate-change/ for the State Sea Level Rise Guidance Document.

Table 3. NRC Sea-Level Rise Projections for California (NRC, 2012)

| TIME PERIOD | NORTH OF CAPE MENDOCINO[14] | SOUTH OF CAPE MENDOCINO |
|---|---|---|
| 2000 – 2030 | -4 – +23 cm<br>(-1.56 – 9 inches) | 4 – 30 cm<br>(1.56 – 11.76 inches) |
| 2000 – 2050 | -3 – + 48 cm<br>(-1.2 – 18.84 inches) | 12 – 61 cm<br>(4.68 – 24 inches) |
| 2000 – 2100 | 10 – 143 cm<br>(3.6 – 56.28 inches) | 42 – 167<br>(16.56 – 65.76 inches) |

The NRC projections break the California coast into two regions – South of Cape Mendocino and North of Cape Mendocino. South of Cape Mendocino, much of the land is experiencing subsidence, which will augment the consequences of rising sea level. For much of the area north of Cape Mendocino, the consequences of rising sea level are being reduced by the vertical land uplift along much of the Cascadia Subduction Zone. However, much of this vertical uplift could change rapidly during the next large Cascadian earthquake. Areas north of Cape Mendocino could experience rapid subsidence of up to 2 meters (about 6 feet) when there is a large earthquake on this active subduction zone. In contrast to the vertical uplift occurring throughout the majority of the area north of Cape Mendocino, Humboldt Bay's North Spit is subsiding and experiencing the highest rate of sea-level rise in the state: a rate of 18.6 inches per century (NOAA, 2013).

Actual sea-level rise in a particular location along the coast will likely vary from these regional projections primarily due to changes in vertical land motion and ocean circulation. The projections also only provide estimated sea-level rise ranges through 2100, although sea level will continue to rise at an accelerating rate beyond the end of the century. As a result, it may be necessary for local governments, applicants, and staff to modify these projections to account for local conditions and specific time periods, using the steps provided in Appendix B.

## B. Physical Impacts of Sea-Level Rise

Continued and accelerated sea-level rise will have widespread adverse consequences for California's coastal resources (See Figure 3), including increased inundation, flooding, coastal erosion, saltwater intrusion, and habitat loss. Absent any preparatory action, an increase in sea level may have serious implications for coastal property, infrastructure, and development; beaches, public access, and recreation areas; coastal habitats, and archeological and paleontological resources; fisheries, ports, and public works facilities; and some ground water aquifers.

[14] Since portions of Humboldt Bay are experiencing subsidence, and thus differ from the regional uplift conditions, the projections for north of Cape Mendocino may not be appropriate for use within parts of Humboldt Bay. See Appendix B for additional discussion about vertical land movement and relative sea-level rise.

Impacts from sea-level rise to the coastal zone include the following:

- **Flooding and inundation:** Low lying coastal areas may experience more frequent flooding (temporary wetting) or inundation (permanent wetting), and the inland extents of 100-year floods may increase. Riverine and coastal waters come together at river mouths, coastal lagoons, and estuaries, and higher water levels at the coast may cause water to back up and increase upstream flooding (Heberger et al., 2009). Drainage systems that outlet close to sea level could have similar problems, and inland areas may become flooded if outfall pipes back up with salt water. In addition, other climate change impacts such as increases in the amount of precipitation falling as rain rather than snow will add to river flooding in some areas.

- **Erosion:** Large sections of the California coast consist of oceanfront cliffs that are often highly susceptible to erosion. With higher sea levels, the amount of time that bluffs are pounded by waves at high tide would increase, causing greater erosion (NRC, 2012). This erosion could lead to landslides and loss of structural and geologic stability of bluff top property, the California Coastal Trail, Highway 1, and other roads and public infrastructure. In 2009, the Pacific Institute estimated that 41 square miles of coastal land between the California-Oregon border and Santa Barbara County could be lost due to increased erosion with 1.4 m of sea-level rise by the year 2100, putting at risk the 14,000 people who live in those areas. Increased erosion will not occur uniformly throughout the state and Mendocino and Humboldt Counties have the greatest areas projected to be lost by erosion. For example, dunes in Humboldt County could erode a distance of nearly 600 m (approximately 2000 feet) by 2100 (Heberger et al., 2009).

- **Changes in sediment supply and movement:** Sediment is important to coastal systems, for example, in forming beaches, mudflats, and as the substrate for wetlands. Sea-level rise will result in changes to sediment availability. Higher water levels and changing precipitation patterns could change erosion and deposition patterns. Losses of sediment could worsen beach erosion and possibly increase the need for beach nourishment projects (adding sand to a beach or other coastal area), as well as decrease the effectiveness and long-term viability of beach nourishment if sand is quickly washed away after being placed on a beach (Griggs, 2010). Sediment supplies in wetland areas will be important for long-term marsh survival. Higher water levels due to sea-level rise, however, may outpace the ability of wetlands to trap sediment and grow vertically (Titus, 1988; Van Dyke, 2012; Ranasinghe et al., 2012).

- **Saltwater intrusion:** An increase in sea level could cause saltwater to enter into ground water resources, or aquifers. Existing research suggests that rising sea level is likely to degrade fresh ground water resources in certain areas, but the degree of impact will vary greatly due to local hydrogeological conditions. Generally, the most vulnerable hydrogeological systems are unconfined aquifers along low-lying coasts, or aquifers that have already experienced overdraft and saline intrusion. In California, saline intrusion into groundwater resources is a problem in multiple areas, including but not limited to the Pajaro Valley (Hanson, 2003), Salinas Valley (Hanson et al., 2002a; MCWRA, 2012.), Oxnard Plain (Izbicki, 1996; Hanson et al., 2002b), and the heavily urbanized coastal plains of Los Angeles and Orange Counties (Ponti et al., 2007; Edwards and Evans, 2002; Nishikawa et al., 2009; Barlow and Reichard, 2010). Ground water sources for coastal agricultural lands may also be susceptible to saltwater intrusion. Additional research is needed to understand the site-specific consequences of sea-level rise and saltwater intrusion to these and other coastal aquifers in California.

## C. Consequences of Sea-Level Rise for Coastal Resources and Development

Some of the consequences of sea-level rise are described below, along with the relevant Coastal Act policies:

- **Coastal development (Sections 30235, 30236, 30250, 30253):** Sea-level rise will increase the likelihood of property damage from flooding, inundation, or extreme waves, and will increase the number of people living in areas exposed to significant flooding. Increased erosion and loss or movement of beach sand will lead to an increase in the spatial extent of eroding bluffs and shorelines, and could increase instability of coastal structures and recreation areas. Levee systems could also experience damage and overtopping from an increase in water levels, extreme wave conditions, or a loss of wetlands, which buffer impacts from high water. The replacement value of property at risk from sea-level rise for the California coast is approximately $36.5 billion (in 2000 dollars, not including San Francisco Bay). The number of people living in areas exposed to flooding from a 100-year flood is estimated to increase by 67% with a 1.4 m increase in sea level (Heberger et al., 2009). According to Heberger et al. (2009), the greatest increases in the number of people vulnerable to flooding will occur in Los Angeles, San Diego, Ventura, Humboldt, and San Luis Obispo counties.

  Impacts to public infrastructure, ports, and industrial development include:

  - **Public infrastructure:** Low-lying roads, wastewater treatment facilities, energy facilities, stormwater infrastructure, and utility infrastructure such as potable water systems and electricity transfer systems are at risk of impaired function due to erosion, flooding, and inundation. Heberger et al. (2009) estimated that 7 wastewater treatment plants; 14 power plants, including one in Humboldt County and 13 in Southern California; and 250 miles of highways, 1500 miles of roads, and 110 miles of railways could be at risk from a 100-year flood with 1.4 meter rise in sea level (Heberger et al., 2009). Facilities and highways located on coastal bluffs subject to erosion will generally become more susceptible in the future. Sections of Highway 1 have already had to be replaced due to erosion, including areas in Monterey Bay, Half Moon Bay, Marin County, and Humboldt County, and the number of sections at risk in the future will likely increase.

  - **Ports (Sections 30703 – 30708):** Sea-level rise could cause a variety of impacts to ports, including flooding and inundation of port infrastructure and damage to piers and marina facilities from wave action and higher water levels. A possible benefit could be a decreased need for dredging. But, higher water levels could increase the difficulty for cargo handling facilities due to the higher vessel position (California Coastal Commission, 2001). Increased water heights could reduce bridge clearance, reducing the size of ships that can access ports or restricting movement of ships to low tides, and potentially increasing throughput times for cargo delivered to ports. Heberger et al. (2009) found that significant flooding from sea-level rise is possible at the Ports of Los Angeles and Long Beach. Given that these two ports handle 45-50% of the containers shipped into the United States, and 77% of goods that leave the state, sea-level rise could affect the efficiency of goods movement, and have serious economic implications for California and the nation (Heberger et al., 2009).

- **Industrial development, refineries, and petrochemical facilities (Sections 30260-30266.5):** Sea-level rise could reduce areas available for siting or expansion of industrial development. Inundation of contaminated lands near industrial development could lead to problems with water quality and polluted runoff. Sea-level rise could lead to an increase in flooding damage of refineries or petrochemical facilities, and impacts from sea-level rise could be an issue when locating or expanding refineries or petrochemical facilities, or when mitigating any adverse environmental effects.

- **Construction altering natural shoreline (Section 30235):** Sea-level rise may lead to an increase in demand for construction of shoreline protection for existing development, public access, and coastal dependent uses in danger of erosion. Shoreline protection devices alter natural shorelines and also generally have negative impacts on beaches, near-shore marine habitat, and scenic and visual qualities of coastal areas.

- **Coastal agriculture (Section 30241- 30243):** Sea-level rise could lead to an increase in flooding and inundation of low-lying agricultural land, saltwater intrusion into agricultural water supplies, and a decrease in the amount of freshwater available for agricultural uses. Flooding of agricultural lands can cause major impacts on local businesses, national food supplies, and the state's economy.

- **Public access and recreation (Sections 30210, 30211, 30213, 30220, 30221):** One of the highest priorities in the Coastal Act is the mandate to maximize public access to the coast. Sea-level rise could lead to a loss of public access and recreational opportunities due to permanent inundation, episodic flooding, or erosion of beaches, recreational areas, or trails. In areas where beaches cannot migrate inland due to development or existing landforms, beaches will become narrower or will disappear completely. Access and functionality of water-oriented activities may also be affected. For instance, sea-level rise, by increasing water levels and altering sediment patterns, could lead to a change in surfing conditions or affect the safety of harbors and marinas (Kornell, 2012).

- **Coastal habitats (Sections 30230, 30231, 30233, 30240):** Coastal habitat areas likely to be affected by sea-level rise include bluffs and cliffs, rocky intertidal areas, beaches, dunes, wetlands, estuaries, lagoons and tidal marshes, tidal flats, eelgrass beds, and tidally influenced streams and rivers. Impacts to wetlands, intertidal areas, beaches, and dunes include:

- **Beaches, dunes, and intertidal areas:** Inundation and increased erosion from sea-level rise could convert habitats from one type to another and generally reduce the amount of nearshore habitat, such as sandy beaches and rocky intertidal areas, available for species. Sea-level rise will cause landward migration of beaches over the long term, and could lead to a rapid increase in the retreat rate of dunes. Beaches with seawalls or other barriers will not be able to migrate landward and the sandy beach areas will gradually become inundated (NRC, 2012). A loss of beach and dune areas will have significant consequences for beach and adjacent inland ecosystems. Beaches and dunes provide critical habitat for species, act as buffers to interior agricultural lands and habitat during storms, and are essential for the persistence of dune habitats (CA Natural Resources Agency, 2009).

  In California, there are many endemic and endangered species that are dependent on bluffs and cliffs, dunes, sandy beaches, rocky intertidal areas, tidal marshes, and other coastal environments. For example, grunion need a sandy beach environment in order to survive, the California clapper rail is dependent on marshes and wetlands, and the black abalone requires rocky intertidal habitat. Nesting, nursery areas, and haul-out sites important for birds, fish, marine mammals and other animals could also disappear as sea levels rise (Funayama et al., 2012).

- **Wetlands:** Sea-level rise will lead to wetland habitat conversion and loss as the intertidal zone shifts inland. Of particular concern is the loss of saltwater marshes from sea-level rise, which have already decreased by about 90% from their historical levels in California (CA Natural Resources Agency, 2010). California's 550 square miles of critical coastal wetland habitat (Heberger et al., 2009, including wetlands in San Francisco Bay) will be converted to open water if they are not able to migrate inland due to natural or anthropogenic barriers. Although migration barriers are plentiful, inland migration of wetlands is possible in some areas. A 1.4 meter increase in sea level would flood 150 square miles of land immediately adjacent to wetlands, which could become future wetlands if that land remains undeveloped (Heberger et al., 2009). Loss or reduction of wetland habitat would impact many plant and animal species, including migratory birds that depend on these habitats as part of the Pacific Flyway. Species that are salt-tolerant may have an advantage as sea-level rise occurs, while species that have narrow salinity and temperature tolerances may have difficulty adapting.

- **Water quality (Section 30231):** Coastal water quality could decrease due to inundation of toxic soils and an increase in nonpoint source pollution from flooding. Sea-level rise could also lead to declines in coastal water quality in several other ways. First, rising seas could impact wastewater facility infrastructure near the coast. In addition to damaging equipment and blocking discharge from coastal outfall structures, floods could force facilities to release untreated wastewater, threatening nearby water quality (Heberger et. al., 2009). Second, sea-level rise could lead to salt water intrusion into valuable ground water aquifers, potentially rendering some existing wells unusable and decreasing the total ground water supply in coastal areas. The extent of salt water intrusion will likely vary based upon local hydrological conditions, with the worst impacts occurring in unconfined aquifers along low-lying coasts that have already experienced overdraft and saline intrusion. This change could force affected communities to turn to more costly water sources such as surface water transfers or desalination. Finally, loss of wetlands could decrease water quality since wetlands improve water quality by slowing and filtering water that flows through them.

- **Biological productivity of coastal waters (Section 30230, 30231):** Sea-level rise could affect biological productivity of coastal waters by changing the types of habitats that are available, which would alter species compositions, and could potentially affect the entire coastal food chain. Changes in water quality can have differing impacts on biological productivity. For instance, decreased water quality due to increased nutrient pollution has been found to increase biological productivity at the base of the food chain to undesirable levels, and has been linked to harmful algal blooms (Caldwell et al., 2013; Kudela, Seeyave, and Cochlan, 2010; Ryan, McManus, and Sullivan, 2010).

- **Archeological and paleontological resources (Section 30244):** Archeological or paleontological resources could be put at risk by inundation, flooding, or by an increase in erosion due to sea-level rise. Areas of traditional cultural significance to California Native American tribes, including villages, religious and ceremonial locations, middens, burial sites, and other areas, could be at risk from sea-level rise. For example, the Santa Barbara Channel area has thousands of archaeological sites dating over 13,000 years that are at risk of being destroyed or altered from small amounts of sea-level rise (Reeder et al., 2010).

For a summary of some of the sea-level rise impacts and potential consequences for the coast, see Figure 3. Many of these are impacts that coastal managers already deal with on a regular basis, and strategies already exist for minimizing impacts from flooding, erosion, saltwater intrusion, and changing sediment patterns. Preparing for sea-level rise involves integrating future projections of sea levels into existing hazard analyses, siting, design, and construction processes, and ecosystem management practices.

**Sea-Level Rise Impacts and Consequences**

**Drivers of Global SLR**

- Expansion of ocean water as temperature increases
- Addition of freshwater to the ocean from melting glaciers and ice sheets
- Addition of freshwater to the ocean from groundwater extraction, use, and discharge

**Drivers of Local/Regional SLR Variability**

- Vertical land movement
- Oceanographic phenomena including El Nino Southern Oscillation (ENSO) and

**Physical Impacts of SLR**

- Inundation (permanent wetting)
- Flooding (temporary wetting)
- Increased erosion and bluff collapse
- Increased tidal prism
- Increased wave heights and force
- Increased saltwater intrusion
- Change in sediment movement patterns

**Summary of Consequences of SLR for Coastal Resources & Development**

**Public Access & Recreation:** Loss of beach areas where beaches cannot migrate inland due to development; inaccessibility of public accessways and recreation sites due to flooding and erosion.

**Coastal Habitats:** Transformation of habitats as intertidal zone shifts inland; loss of wetlands and other habitats where areas cannot migrate up or inland due to inland barriers such as coastal development.

**Coastal Agriculture:** Increase in flooding and inundation of low-lying agricultural lands; saltwater intrusion into agricultural water supplies; potential decrease in amount of freshwater available for agricultural uses, or inability of wetlands to keep pace vertically with rising water levels.

**Cultural Resources:** Archeological and paleontological sites, including many Native American villages, religious and ceremonial locations, burial sites, and other areas could be at risk from sea-level rise.

**Public infrastructure:** Low-lying roads, wastewater treatment facilities, energy facilities, stormwater infrastructure, potable water systems, and electricity transfer systems are at risk of inundation and flooding, and impaired function. Infrastructure located on eroding bluffs is also subject to increased geologic hazards.

**Ports & Marinas:** Possible decrease in need for dredging; damage to piers and marina facilities from greater uplift forces and higher water levels; potential difference in heights between ships, cargo handling facilities and drydock/ ship repair facilities.

**Coastal Development:** Greater likelihood of tidal damage, flooding, inundation, and extreme waves, which could lead to loss of property or physical injury; instability from increased erosion and loss/movement of beach sand; increased areas exposed to a 100-year flood.

Figure 3. Summary of Sea-Level Rise Impacts and Consequences